Magnitude determination using strong ground-motion attenuation in earthquake early warning

Ting-Li Lin¹ and Yih-Min Wu¹

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[1] We use 1661 strong-motion accelerograms with peak ground acceleration (PGA) larger than 80 Gal (1 Gal = 1.0 cm/s²) from 77 earthquakes recorded by the Taiwan Strong Motion Instrumentation Program (TSMIP) stations to derive a strong-motion attenuation relationship. This relationship can be used to dynamically define a “Mpga magnitude” for earthquakes using earthquake locations determined by earthquake early warning process. The Mpga magnitude using this strong-motion attenuation relationship corresponds well with Ms given a sufficient number of PGA readings. MEMS (Micro Electro Mechanical Systems) acceleration sensor could be widely used for ground motion monitoring purposes. Thus, we propose that once a large earthquake has begun, that we might be able to use strong, near-field (tens of kilometers) PGA values to quickly estimate the earthquake’s magnitude, which would improve earthquake early warning. Citation: Lin, T.-L., and Y.-M. Wu (2010), Magnitude determination using strong ground-motion attenuation in earthquake early warning, Geophys. Res. Lett., 37, L07304, doi:10.1029/2010GL042502.

1. Introduction

[2] When a large earthquake occurs, an earthquake early warning (EEW) system can alert populations, sensitive transportation systems, ahead of the arrival of strong ground shaking. The idea of an EEW system was proposed more than one hundred years ago by Cooper [1868] for San Francisco, California. An early warning leading time can be a few seconds to a few tens of seconds depending on the distance between the earthquake and the target warning areas. Although this warning time window might seem short, it can be critical, as even a few seconds are sufficient to initiate pre-programmed EEW emergency safety responses. Therefore, EEW is a practical, effective approach to seismic risk mitigation on a short time-scale [Kanamori et al., 1997; Teng et al., 1997; Wu and Teng, 2002; Allen and Kanamori, 2003; Kanamori, 2005] as compared to the longer time-scale earthquake prediction.

[3] The two most commonly used types of EEW are regional and onsite warning systems. In regional EEW, the ground shaking characteristics recorded by seismic sensors closest to the earthquake rupture are used to predict strong ground motions at more distant target areas. In onsite EEW, the initial P-wave motion at a given site is used to predict the ground motions of the later S and surface waves (which commonly have higher amplitudes or destructive energy than that of the initial P-wave motion) at the same site or region where the onsite warning instruments are operating.

[4] An onsite EEW system must predict the earthquake’s magnitude, and the ensuing peak ground motion rapidly and reliably. An average period parameter (τc) from the initial 3 seconds of the P-wave [Kanamori, 2005; Wu and Kanamori, 2005a; Wu et al., 2007a], originally proposed by Nakamura [1988], and Allen and Kanamori [2003], can be used to predict the size of an earthquake. Wu and Kanamori [2008a, 2008b] showed that earthquake magnitude (Ms) could be estimated from τc for strong motion data from the Japan, Taiwan, and southern California records. Wu and Kanamori [2005b] and Wu et al. [2007a] showed that the peak initial displacement amplitude, Pd, from the first 3 seconds of the P-wave correlates well with the peak ground-motion velocity, PGV, observed at the same site, using strong motion data from Taiwan and southern California, respectively. Combining τc and Pd (τc × Pd), Wu and Kanamori [2005b] demonstrated that τc × Pd provides a more reliable indicator for identifying damaging earthquakes.

[5] For regional EEW, rapid and reliable determination of earthquake magnitude is more difficult than the estimation of other parameters (such as earthquake location) because the shear wave portion may not completely arrive in a few to ten seconds time window [Wu and Zhao, 2006]. Using the real-time strong-motion network in Taiwan, Wu et al. [1998] proposed the Mt10 method based on the first 10 seconds of the P-wave to determine earthquake magnitude that is well correlated to the local magnitude Mt for regional EEW purpose. In the regional EEW approach, Wu and Zhao [2006] showed, for earthquakes in southern California, that Pd is also a robust measurement for estimating the earthquake magnitude. Onsite EEW systems under development in Taiwan and southern California will use the τc method for magnitude determination.

[6] This study provides a novel, experimental concept to rapidly determine earthquake magnitude using strong ground-motion attenuation once an earthquake location is determined by the on-site [Odaka et al., 2003] and regional [Rydelek and Pujol, 2004; Horiuchi et al., 2005; Cua and Heaton, 2007; Wurman et al., 2007] EEW techniques. We first define a strong ground-motion attenuation relationship for Taiwan for large crustal earthquakes with PGA observations larger than 80 Gal. Then, we use the resulting strong motion attenuation relationship to invert for the Mpga magnitude. Our estimated Mpga magnitudes agree well with Ms for large earthquakes with sufficient numbers of PGA observations. We propose that the magnitude determination method presented in this study might be integrated into current operating EEW rapid reporting systems to provide...
For this study, we used shallow crustal earthquakes with PGA values (on at least one of the three components) exceeding 80 Gal, recorded by the TSMIP stations from 1993 to 2008; since either EEW or rapid reporting is principally and practically applied to large damaging earthquakes. A PGA value larger than 80-Gal corresponds to a CWB intensity scale of V (80–250 Gal) in Taiwan [Wu et al., 2003], or to a Modified Mercalli intensity scale [Wald et al., 1999] value of VI (92–180 Gal). Large, shallow inland earthquakes often cause the most serious damage. We assume that 42 km is the average depth to the Moho interface in Taiwan [Tomohrde and Nowack, 2000; Wu et al. 2007b], and define a shallow earthquake as one having a focal depth of less than 42 km. In fact, most inland or offshore (distance to shoreline < 5 km) earthquakes that cause ground shaking to a maximum PGA > 80 Gal have focal depths shallower than 25 km in Taiwan. We ended up with 1661 PGA readings larger than 80 Gal recorded by TSMIP stations, from 77 crustal earthquakes (Figure 1 and Table S1) to use to derive the strong ground-motion attenuation relationship for this study. We then used these observations to invert for the constants in our assumed “$M_{PGA}$ magnitude” parameterization.

We chose a strong ground-motion attenuation relationship of the from:

$$\log_{10} PGA = a \log_{10}(r) + bM + c,$$

(1)

where $r$ is the epicenter distance in km, $M$ is the moment magnitude ($M_w$), $a$ and $b$ are empirical coefficients for geometrical spreading and magnitude, respectively, and $c$ is a constant. Coefficients $a$, $b$, and $c$ are the parameters to be determined from a regression analysis. The use of $M_w$ instead of local magnitude ($M_l$) avoids the magnitude saturation of large earthquakes, which is particularly important as EEW and rapid reporting are mostly directed toward larger earthquakes. We have adopted the $M_w$ that were reported by Harvard centroid moment tensor (CMT) project. For earthquakes without Harvard CMT solutions, mostly smaller than $M_w$ 5.3, we have used the empirical equation (equation (2)) to convert $M_l$ to $M_w$ [Chen and Tsai, 2008]:

$$M_l = -0.24 + 1.07M_w \pm 0.31.$$  

(2)

As these earthquakes are too small to saturate $M_l$, we assume that this formula provides a good estimate of $M_w$ for this subset of low magnitude events. The epicenter distance ($r$) is used because most large damaging earthquakes in Taiwan are located in the shallow crust and in the current processes of EEW, the estimation of epicenter location might be more practical and accurate than real time estimates of hypocentral location.

Equation (1) can be rewritten in matrix form as:

$$\begin{bmatrix}
\log_{10} r_1 & M_1 & 1 \\
\log_{10} r_2 & M_1 & 1 \\
\vdots & \vdots & \vdots \\
\log_{10} r_{1661} & M_{17} & 1
\end{bmatrix} \begin{bmatrix}
a \\
b \\
c
\end{bmatrix} = \begin{bmatrix}
\log_{10} PGA_1 \\
\log_{10} PGA_2 \\
\vdots \\
\log_{10} PGA_{1661}
\end{bmatrix}$$

(3)

or $Gm = d$. Equation (3) presents a typical overdetermined inversion problem. The vector of unknowns ($m$) were found
through generalized inverse matrix of $G$ ($G^{-g}$) using singular value decomposition (SVD) [Menke, 1984; Miao and Langston, 2007]. Unlike most common attenuation relationships, anelastic attenuation (linear term) is not considered in the right-hand side of equation (1). This is because we found that variances (standard deviations) of the model parameters ($a$ and $c$) significantly increase in the SVD computations if we include this term. Moreover, in studies of $M_L$ determination [Wu et al., 2005] and $Pd$ attenuation [Wu and Zhao, 2006], both found that the linear term is not statistically significant. Using 1661 PGA readings (> 80 Gal) from 77 events recorded by the dense TSMIP stations in Taiwan, we thus obtain a strong ground-motion attenuation relationship of:

$$\log_{10} PGA = -0.395 \log_{10}(r) + 0.125M + 1.979 \pm 0.161. \quad (4)$$

The standard deviation (0.161) in equation (4) is one standard deviation of the normal distribution that best fits the frequency of $\log_{10} PGA$ residuals (Figure 2). Note that for the PGA readings observed at epicenter distances less than 3 km (i.e., high PGA) are not used in the SVD inversion since these PGA readings usually have abnormal residuals. Figures 2b and 2c indicate that in general the PGA residuals increase as the epicenter distances and the values of $\log_{10} PGA$ increase.

3. Magnitude Determination

[12] Given an epicenter location produced by either a regional or an onsite EEW system immediately after the occurrence of a large earthquake; the $M_{pga}$ magnitude can be simultaneously and dynamically estimated by solving for $M$ in equation (4) for each PGA observation as it becomes available. Figure 3 gives four examples of the $M_{pga}$ magnitude history in real time given by equation (4), with increasing numbers of PGA observations, compared to the reported $M_w$ magnitude for the event. Figure 3a is an example for the 1999 Chi-Chi, Taiwan earthquake ($M_w = 7.6$) which is to date the largest inland recorded event, responsible for the largest number of death, and damage in Taiwan’s natural hazard history. During the Chi-Chi earthquake main shock, a total of 227 acceleration records having PGA values larger than 80 Gal were registered by the TSMIP stations. We consider all four example earthquakes to be large enough to test our implementation of an EEW and rapid reporting system.

[13] The $M_{pga}$ magnitude, resulting from our inversion of the strong-motion attenuation relationship (equation (4)) generally corresponds well with the reported $M_w$ magnitude (Figure 3). As the number of PGA recordings increases for a given event, its $M_{pga}$ magnitude approaches the reported $M_w$ magnitude for that earthquake. In general, about 20–30 PGA recordings provide a stable estimate of $M_w$, suitable for reporting as part of an EEW system. The distribution maps of PGA recording (Figure 3) show that given the current TSMIP station density, an area enclosed by a circle of a radius of about 50 km will provide a satisfactory number of PGA readings to produce a stable $M_{pga}$. Even though PGA values smaller than 80 Gal were not used to obtain equation (4), the $M_{pga}$ magnitudes agree well with the reported $M_w$ magnitudes.

4. Discussion

[14] EEW and rapid reporting systems are applied to earthquakes large enough to cause disastrous damages. Therefore, it is desirable to have rapid earthquake magnitude determinations that are accurate for the very large earthquakes (says $M_w > 6.5$). Figures 4a and 4b compare $M_{pga}$ magnitudes with $M_w$ magnitudes for earthquakes larger than $M_w = 6.0$, and for those larger than $M_w = 6.0$, respectively. Figure 4 indicates that the $M_{pga}$ magnitudes estimated from the PGA values for the earthquakes of $M_w > 6.0$ have the smaller standard deviations (SD) than those for the earthquakes of $M_w > 4.5$. We attribute this result to the larger

![Figure 2.](image-url)
Figure 3. (a–d) The maps of the TSMIP stations recording the PGA values larger than 80 Gal and the relation between the $M_{pga}$ magnitude and the numbers of the PGA recording for the four large earthquakes. The crosses and circles in the maps indicate the epicenters and the TSMIP station locations with the PGA values larger than 80 Gal. The close circles indicate the closest 50 stations to the epicenters.

Figure 4. Comparisons of the $M_{pga}$ magnitude to $M_w$ magnitude for earthquakes larger than (a) $M_w = 4.5$ and (b) $M_w = 6.0$, respectively.
number of PGA recordings and to the better epicenter distance coverage for the larger magnitude earthquakes. Note that in Figure 4 the number of the PGA recordings of each earthquake is required to be greater than 20 recordings. Due to the lack of events with $M_w > 7.0$, it is difficult to identify the magnitude in this study.

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